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13. ABSTRACT (Maximum 200 words)

The primary objective of the Advanced Manufacturing Institute (AMI) at Stevens is to increase American industry's competitiveness through the development, validation, and implementation of concurrent engineering techniques in strategically targeted areas of existing and emerging technologies. The AMI carries out a multidisciplinary program of research, development, education, and technology transfer addressing the use of concurrent engineering practices to create a competitive manufacturing enterprise in specific application areas, such as injection molded polymer-based composites. The AMI research effort has targeted the development of automated design tools for the manufacture of polymer-based composite parts.

The U. S. Department of Defense grant (DAAL03-91-G-0196) has been used to implement a graduate and industrial/research program in concurrent engineering at Stevens, in addition to building the infrastructure that would allow for these practices to be observed and implemented on a laboratory scale. More specifically, this grant has been used, in part, for a program: to support resident engineers from industry; to renovate a facility to house AMI; and to acquire hardware and software to support the education and research programs in concurrent engineering.

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THE ADVANCED MANUFACTURING INSTITUTE

Final Report

for

ARO Grant Number

DAAL03-91-G-0196

STEVENS INSTITUTE OF TECHNOLOGY
Castle Point on the Hudson
Hoboken, New Jersey 07030

January 19, 2001

EXECUTIVE SUMMARY:

The primary objective of the Advanced Manufacturing Institute (AMI) at Stevens is to increase American industry's competitiveness through the development, validation, and implementation of concurrent engineering techniques in strategically targeted areas of existing and emerging technologies. Concurrent engineering is an approach to product development that simultaneously considers manufacturing techniques, performance specifications, material properties, reliability, and cost at the initial stage of design. Controllable design and manufacturing variables may then be optimized in an efficient and systematic manner, resulting in significant quality and cost benefits.

The AMI carries out a multi-disciplinary program of research, development, education, and technolgy transfer addressing the use of concurrent engineering practices to create a competitive manufacturing enterprise in specific applications areas such as injection molded polymer based composites. The AMI research effort has targeted the development of automated design tools for the manufacture of polymer-based composite parts.

The U. S. Department of Defense grant (DAAL03-91-G-0196) has been used to implement a graduate and industrial/research program in concurrent engineering at Stevens, in addition to building the infrastructure that would allow for these practices to be observed and implemented on a laboratory scale. More specifically, this grant has been used, in part, for a program to support resident engineers from industry; to renovate a facility to house AMI, and to acquire hardware and software to support the education and research programs in concurrent engineering.

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I. INTRODUCTION

Manufacturing accounts for more than 20 percent of our Gross National Product. It represents about 60 percent of exports and 75 percent of imports. While many U.S. industries had near monopolies in the period following World War II, approximately 70 percent of everything now produced in this country is subject to foreign competition. There is now a recognized national need for improvement in the way products are designed and manufactured.

A. The Concurrent Engineering Concept

Concurrent engineering is a new model for product development and manufacture. It is a break from the traditional, sequential procedure of product design followed by manufacturing process design and final implementation that is illustrated in Figure 1. The practice has been shown to establish upwards of seventy percent of the ultimate product cost before ten percent of the design has been completed, as presented in Figure 2, that summarizes findings of an auto industry survey. Instead of handling issues as they arise in the sequential evolution of the development cycle, concurrent engineering evaluates all factors simultaneously. All aspects germane to the delivery of new or improved products, responsive to customer needs are considered in parallel, as depicted in Figure 3. Manufacturing costs are postponed until the development process is near conclusion, rather than escalated by poor design decisions committed to long before production. Concurrent engineering complements modern manufacturing techniques like flexible computer integrated manufacturing (FCIM), just-in-time (JIT) manufacturing, statistical process/quality control (SPC/SQC), and computer aided design and computer aided manufacturing (CAD/CAM).

There are some success stories for concurrent engineering - the Ford Taurus and the IBM Pro Printer are two frequently cited examples. In these cases, concurrent engineering was

realized through a project-team approach to design with both examples drawn from the final, or assembly stage of the manufacturing pipeline. To deal with the ultimate complexity of a fully concurrently engineered transition from feed materials to final product, this approach does not suffice.

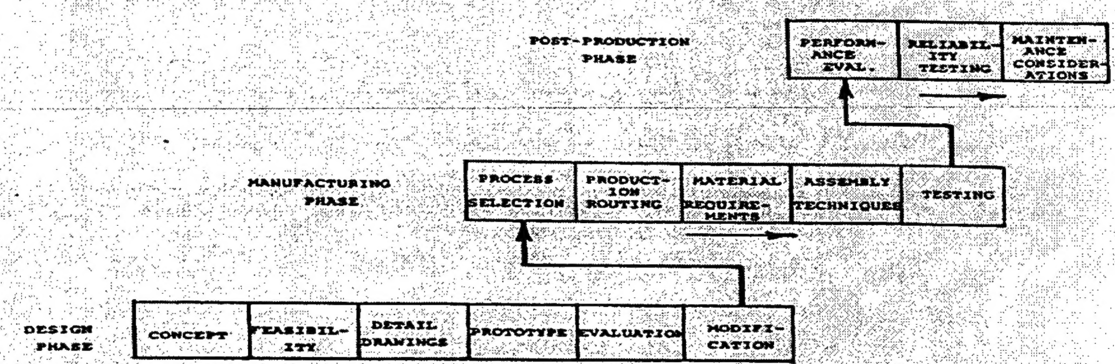


FIGURE 1: TRADITIONAL DESIGN AND MANUFACTURING PROCESS

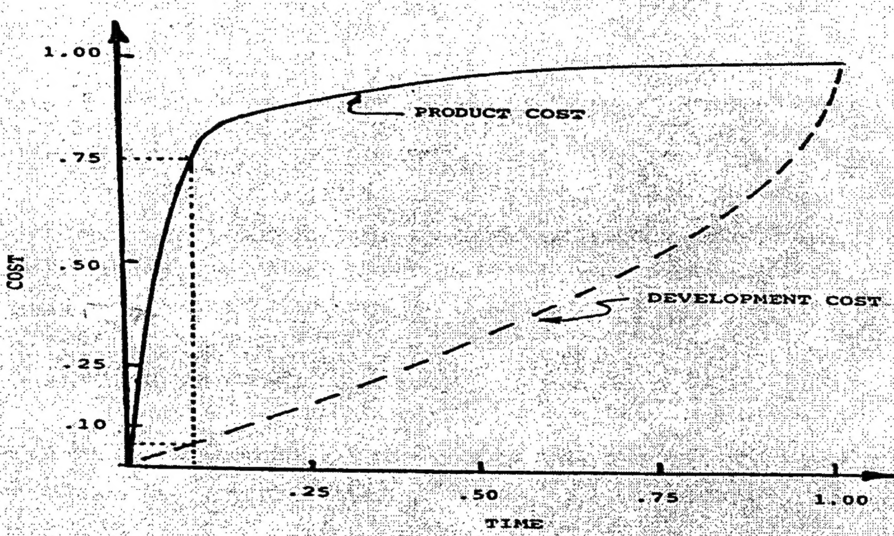


FIGURE 2: DEVELOPMENT COST vs PRODUCT COST FOR AUTOMOBILE PARTS

There are simply too many interwoven factors, and too many independent subcontracting firms for one team to deal with. There are also too many new designs. Manufacturing has accepted a consumer- driven posture that means custom tailored products for niche markets and regular delivery of new products. Just as shop floor automation increased productivity by reducing *manual* labor, automation of many elements of the decision making process is needed to improve *intellectual* productivity.

A new and powerful type of computer modeling utilizing decision aids is a key to realizing concurrent engineering on a broader scale. This innovative approach, now under development at AMI, transcends the analytical models already familiar to "hard-engineering" applications, or the empirical models common to the social scientists. Rigorous simulations, based upon first principles, provide in-depth process insights that are then generalized to design rules. Modular calculations set the selection of alternative design strategies.

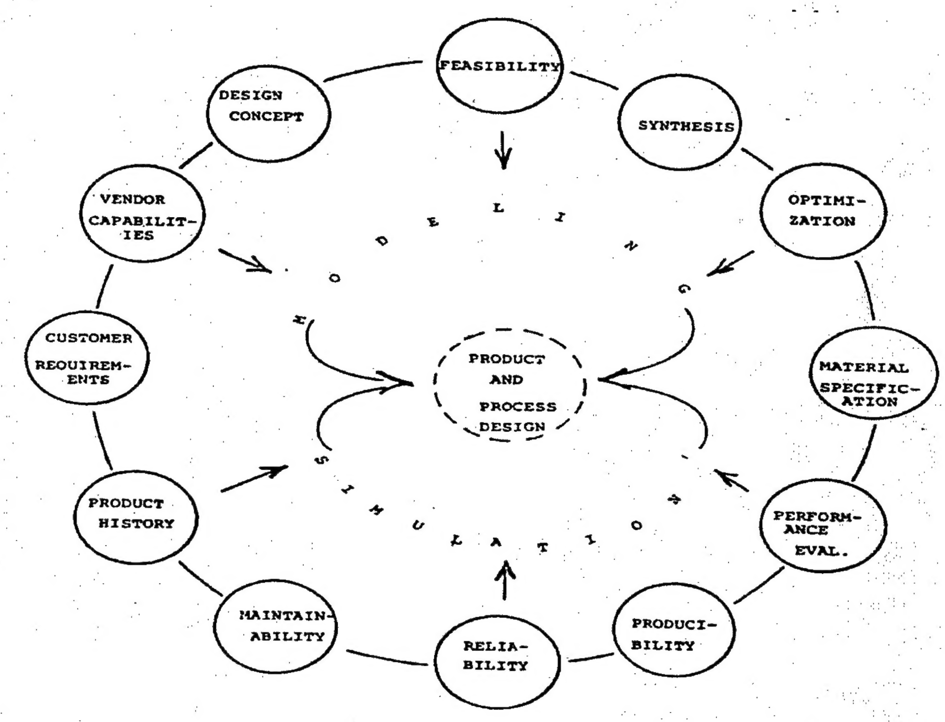


FIGURE 3: THE CONCURRENT ENGINEERING PROCESS

B. Rationale of the AMI Program

The first application area being addressed by the AMI program is the concurrent engineering of polymer and polymer composite products. Concurrent engineering concepts and methods are developed enabling innovative product designs using engineering thermoplastics. Concurrent engineering leads to competitive manufacturing of a wide range of products made from high performance polymers including personal electronics, medical implants and structural components for automobiles, watercraft, and airplanes.

The Advanced Manufacturing Institute houses a flexible polymer manufacturing center that has been staffed with engineering professionals capable of resolving the wide ranging problems that are encountered in manufacturing with high performance polymers. AMI has been equipped with a process line for the major fabrication steps of injection molded components. A focused program of design and manufacturing research is being pursued to enable consulting and contract research and development services for government and industry.

Engineering polymers differ from commodity plastics by achieving high strength to weight ratios, resistance to high temperatures and corrosive environments, optical purity, and bio-degradability. Superior performance is a consequence of custom tailored *microstructure* that is developed by virtue of processing, and in-situ chemical modification. Product performance and process design are inseparable, making a concurrent engineering scheme especially appealing for manufacturing with these materials.

To take full advantage of high performance polymers, the evolution of microstructure during processing and forming must be understood from basic principles, which apply to a wide variety of processing conditions and a broad

class of feedstock materials. This demands in-depth knowledge of material and machine interactions during the elementary steps such as solids transport, melting, mixing, reaction, and pumping, which are common to all processing equipment. This knowledge leads to improved manufacturing in a variety of products. Several important opportunities are already apparent, including:

- Improved technology for micro-chip packaging
- Continuous extrusion techniques for highly filled solid propellants
- Manufacturing technology for the Air Force's Advanced Tactical Fighter constructed from reinforced thermoplastics
- Development of plastics gears for applications in power transmission
- Design of plastic sonar buoys
- Development of continuous rubber compounding for high performance tank pads, tires, o-ring and drive belts.

Manufacturing processes for polymer parts are sufficiently different from those of machined parts that much of current shop-floor automation technology is not immediately applicable. In polymer production, manual operations are not excessive, and processing equipment is intrinsically capable of delivering a wide range of end-products from a small set of machine types. Flexible operation comes from the ability of one fabrication line to process many different *materials* rather than the ability of a manufacturing cell to produce a variety of *geometries.* To accomplish process-line versatility, it is necessary to close the open loop between material properties and machine parameters.

The presence of a real-life manufacturing operation at Stevens represents a significant asset to the curricular programs in engineering, science, and management. It offers a dynamic ability to apply classroom lessons to a broad range of inter-disciplinary problems. The use of structured and quantitative methodology for design clearly elucidates the role of engineering theory in

engineering practice. Students learn design by doing design. The impact is not limited to strictly technical concerns. Driven by a need to solve real problems within a time scale consistent with the demands of the on-going manufacturing process, project teamwork helps students develop improved interpersonal skills.

II. TECHNICAL PROGRAM

A. Objective

The objective of the program undertaken through the current grant was to facilitate the overall AMI goal of improving the competitiveness of American industry. These activities included:

- Facility renovation
- Equipment acquisition
- Establishment of educational and technology transfer mechanisms

A detailed description of each of these activities follows.

B. Facility Renovation

The Advanced Manufacturing Institute is housed in the Carnegie building on Sixth and Hudson Street, in Hoboken New Jersey. A schematic layout of the building, outlining the various functional areas of AMI, is shown in Figure 4. Originally constructed at the turn of the century, it has approximately 17,500 net square feet of floor space on three floors. Substantial renovation was carried out to suit the new set of requirements presented by the institute's activities. The focus of the architectural plan was to preserve the best of the old while supplementing with the best of the new. The structural integrity and architectural detail are a monument to the rich heritage of industrial progress of the last century, and were maintained as such. Inside, the Carnegie Building is now the setting for

an integrated research and production facility featuring high technology process and computational equipment. Even here, though, attention is given to a harmonious blend of old and new; this is a restoration, not a wholesale demolition and reconstruction.

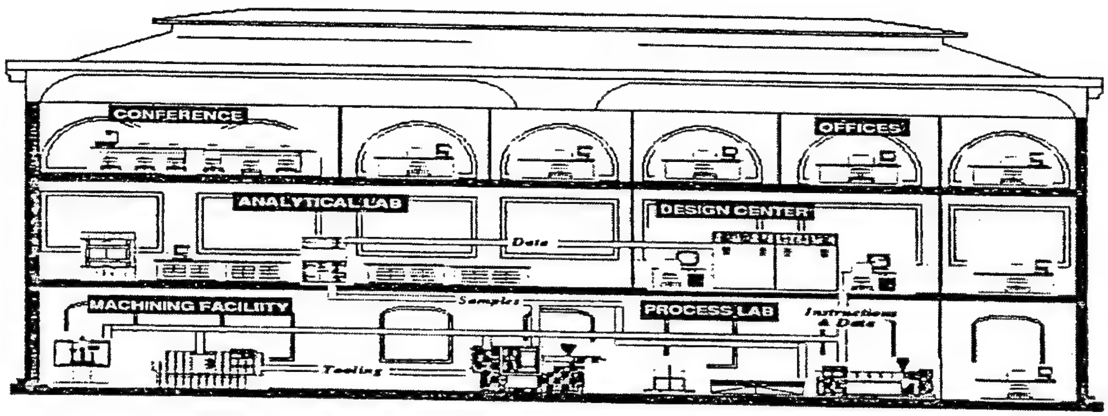


FIGURE 4: ELEVATION OF CARNEGIE BUILDING: BUILT IN 1901 WITH A GIFT FROM ANDREW CARNEGIE

A schematic of the floor-by-floor usage, and the layout is presented in Figure 5(a-d). In the process of renovation several structural issues needed to be addressed to accommodate the increased floor loading imposed by the housing of processing and machining equipment. The first floor foundation (Figure 5a) has been strengthened by the pouring of a new concrete floor. The load bearing capacity of the second floor supports has been upgraded to allow use of this space for medium size equipment (mostly computer hardware). The building was also in need of a general “facelift” which included tuck pointing of exterior brickwork, steam cleaning of a century of grime, and replacement of broken windows with energy efficient designs consistent with the building's architecture.

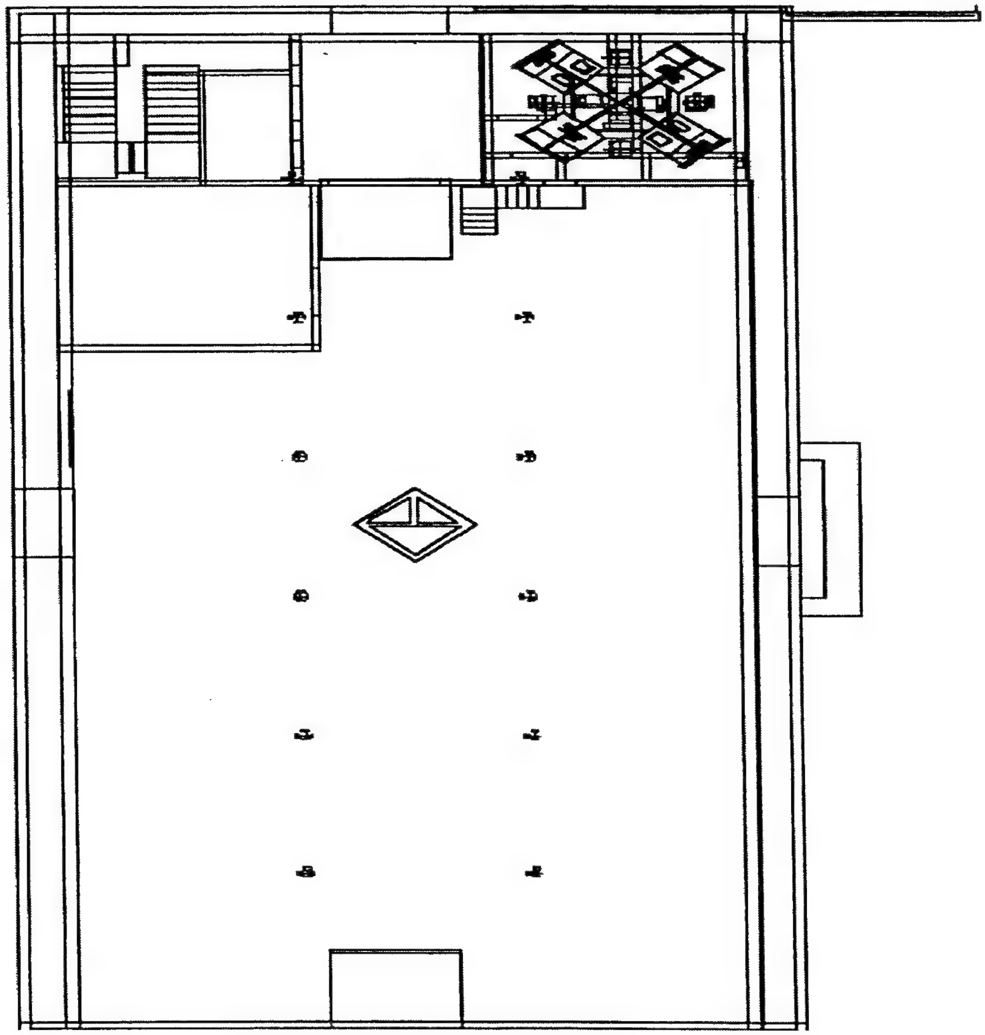


Figure 5a: First Floor Layout Manufacturing & Prototyping Facility

The basic utilities service was up-rated in light of the increased utilization planned for the building. The power supply (440V for most process equipment) has been upgraded on the first floor. Wiring for the campus local area network has been extended throughout the facility. Exhaust hoods for the analytical lab and reactive extrusion cell were added. A new HVAC system also installed to provide for year-round office occupancy and accommodate sensitive computer equipment and modern automated machinery in a sweatshop setting. The room air exchange caused by exhaust hoods places an extra burden upon HVAC requirements and the HVAC system has been appropriately sized to accommodate the plastics processing equipment specific needs.

Large scale process and machining equipment were placed on the first floor to minimize the need for a complete and expensive structural reinforcement of the upper levels. An elevator has been installed to facilitate processing and computer equipment transfers from floor to floor. The elevator also ensures handicap access to all three levels of the installation. The first floor contains a limited amount of office space for shop floor personnel, and has a supply room with external access.

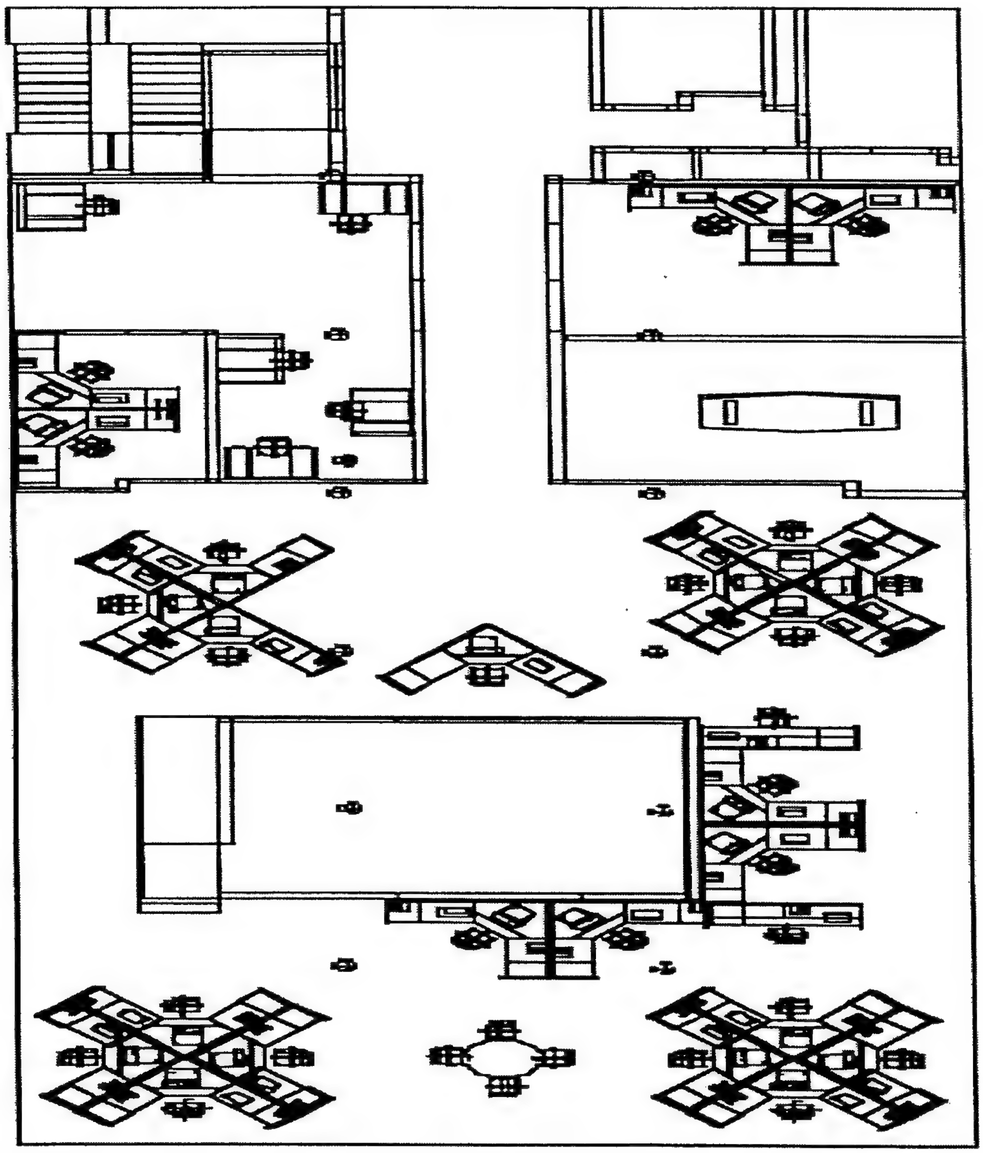


Figure 5b: Second Floor Layout: Computer Center & Work Areas

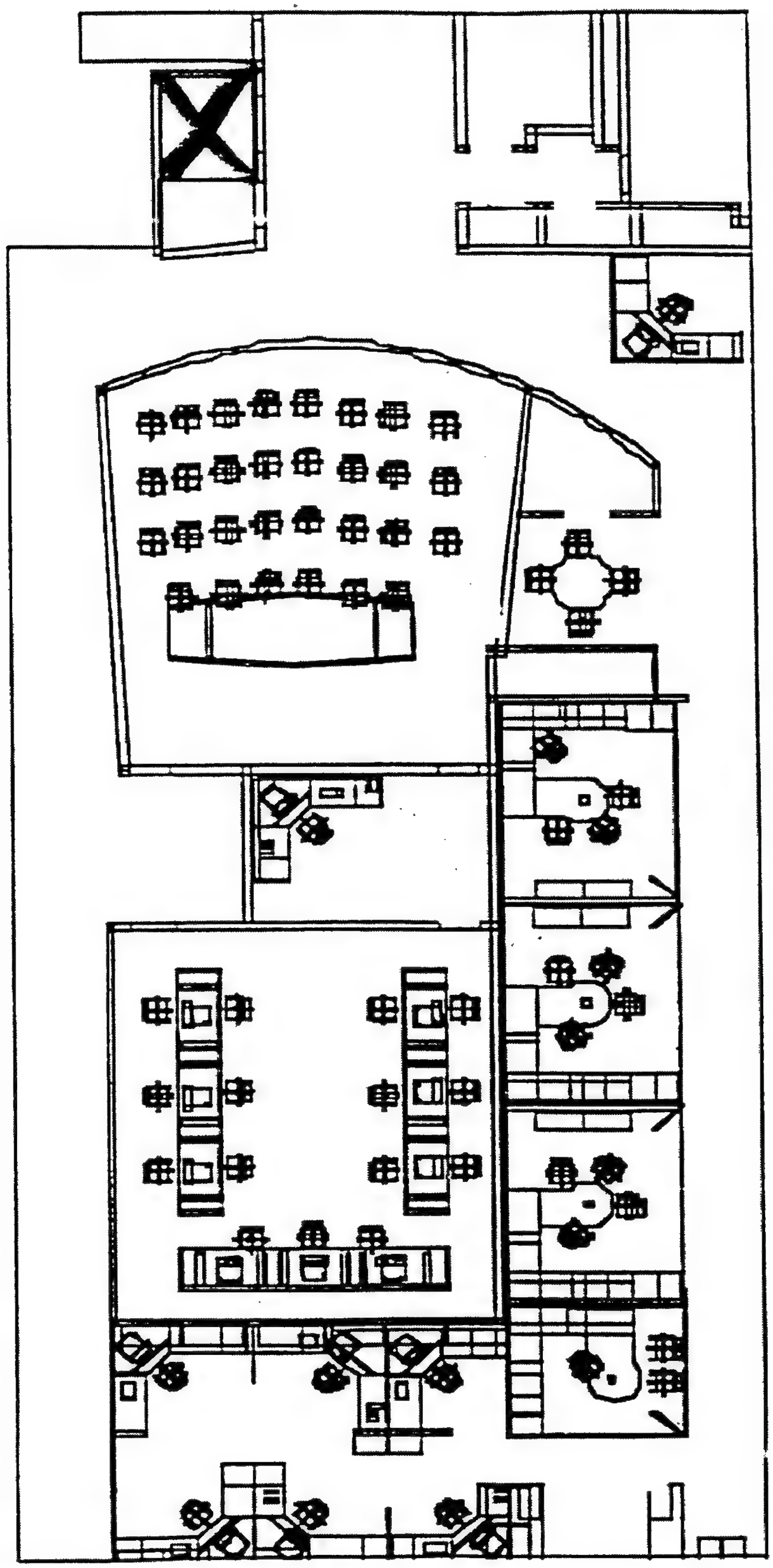


Figure 5c: Third Floor Layout: Auditorium,
Classroom and Offices

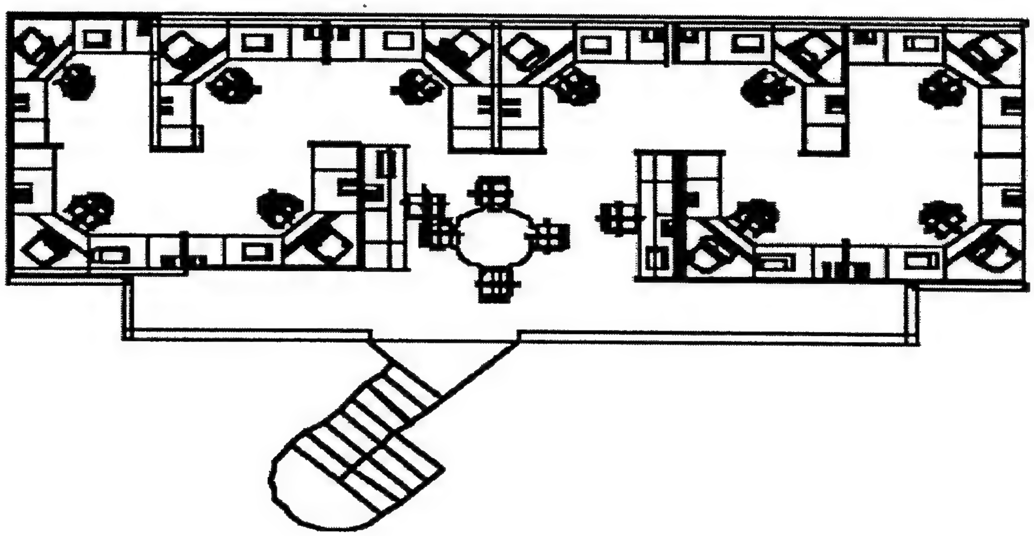


Figure 5d: Second Floor Mezzanine Layout: Workstation Areas

The free standing analytical equipment and the automated testing and analysis cells reside on the second floor. All of the free standing analytical equipment and testing cells have been networked to give centralized data storage and manipulation. Computer facilities are also housed on the second floor. State-of-the-art workstations, vector and array processing mini-computers, graphics animation supercomputers, servers and a variety of personal computers processing supply the computing resources to the concurrent engineering activities. This equipment requires supplementary climate control, and a raised floor configuration has proven advantageous to flexible use of the floor space. Office space for the analytical lab manager, and software professionals is being located on the second floor.

Offices and conference rooms are in the top floor of the facility. All professional and support staff are being linked by the local area network. Office automation has been implemented in pursuit of a "paperless office", with document processing, electronic mail, desktop publishing, and financial management software blending with continuous monitoring of shop floor activities. A modern conference room with a computer integrated audio-visual

presentation system has been created to showcase the institute's activities. Conference rooms provide classroom space for industrial short courses and seminars. The redistribution of space on the second and third floors required demolition of most non-load bearing walls, and framing of the new layout. Details of the floor lay-out and office space configuration are shown in Figures 5a-5d. Additional matching funds of $1,300,000 have been provided to Stevens Institute of Technology, by the New Jersey Department of Higher Education to complete the facility renovation project.

C. Equipment Acquisition

The principal components of the AMI, as shown in Figure 6, are the Polymer Processing Institute (PPI), the Automated Machining Facility(AMF), and the Center for Design Concepts (CDC). In addition to the central computing equipment needed to carry out the modeling, analysis, and control functions of the program (DEC 6500 V, DEC 9300 V, DEC workstations, as shown in figure 13), that was purchased under this grant to satisfy the needs of CDC, the following manufacturing hardware have been obtained in order to appropriately retrofit the PPI and AMF components of AMI:

- Electric-Discharge Machining (EDM) Center
  To be used in the manufacture of molds and mold inserts (see Figure 7a depicting the Robo-form EDM machine housed in the facility, and Figure 7b shown a close-up view of the sinker head in operation)
- Coordinate Measuring Machine (CMM)
  Required for automated quality control and verification of product dimensions (Figure 8 shows the acquired Brown & Sharp model measuring inspecting an injection molded SRAW warhead)
- A Vertical Machining Center and a Turning Center
  A computer-controlled, four axis Cincinnati Milacron milling center and a Cincinnati Milacron turning center with the capability of performing automated tool change and workpiece orientation were purchased to facilitate the on-site fabrication of injection molding tools. (Figure 9 shows

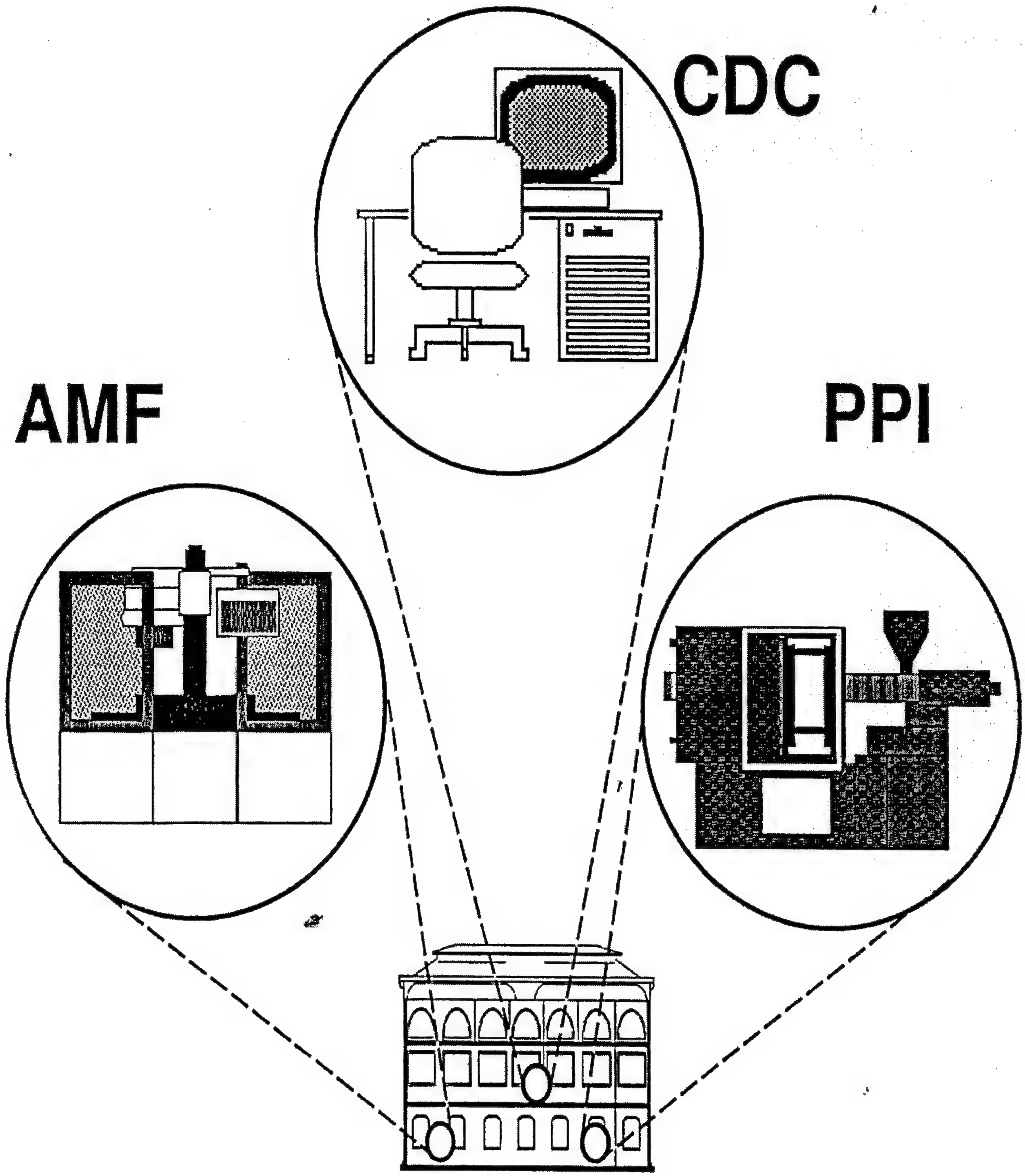


Figure 6: Schematic of the Carnegie Laboratory Building depicting the Location of the Various Centers of Activity within AMI

AMF: Automated Machining Facility
CDC: Center for Design Concepts
PPI: Polymer Processing Institute

shows AMI personnel reviewing injection mold designs during tooling fabrication, while Figure 10 depicts partial views of the equipment housed in the first floor of the Carnegie building facilitating tooling fabrication, situated adjacent to the injection molding equipment)

- Automated Injection Molding Machine & related peripherals
  A 300 ton capacity Cincinnati Milacron molding machine with automated control of process parameters and networking capability. Figure 11 shows the injection molding center and the associated peripherals in the background)
- Stereolithography Machine
  A SLA-250 rapid prototyping machine to be used in the automated fabrication of sample parts and molds for fast-prototyping (see figure 12 below)

The computer-based design center (see Figure 13) is where all comes together. State of the art computer software and hardware, production and testing facilities, form the basis for a "learning factory", where clients and students work together with the AMI professional staff on specific automated concurrent engineering projects.

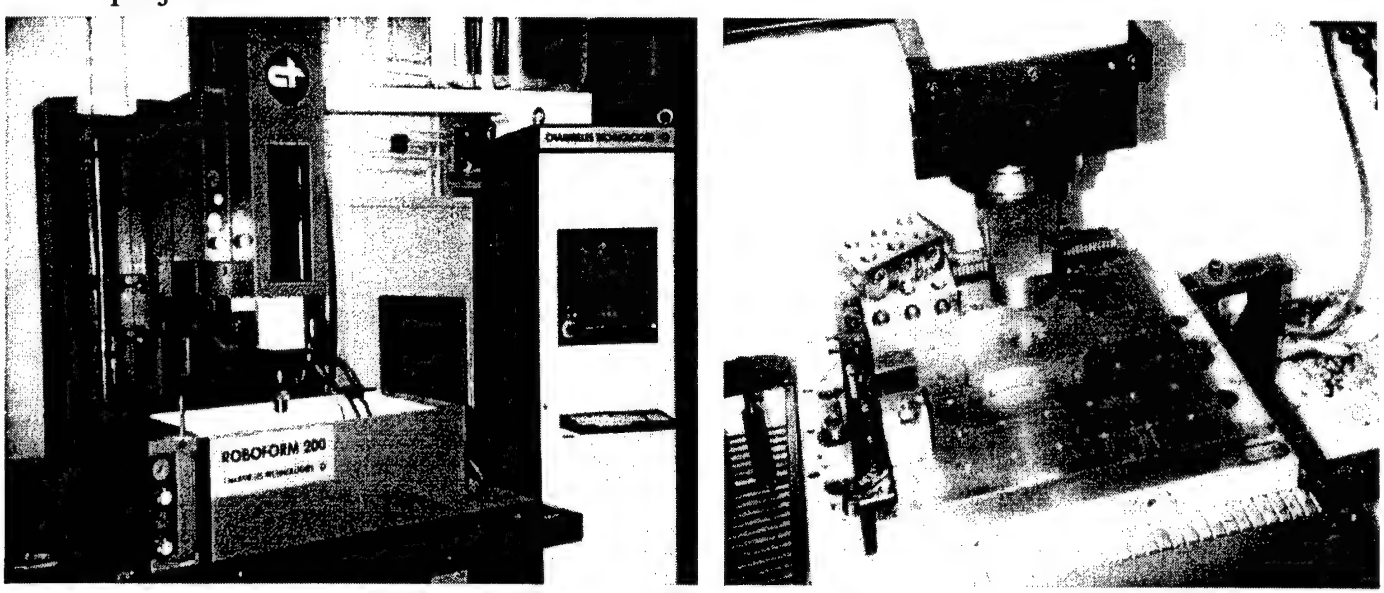
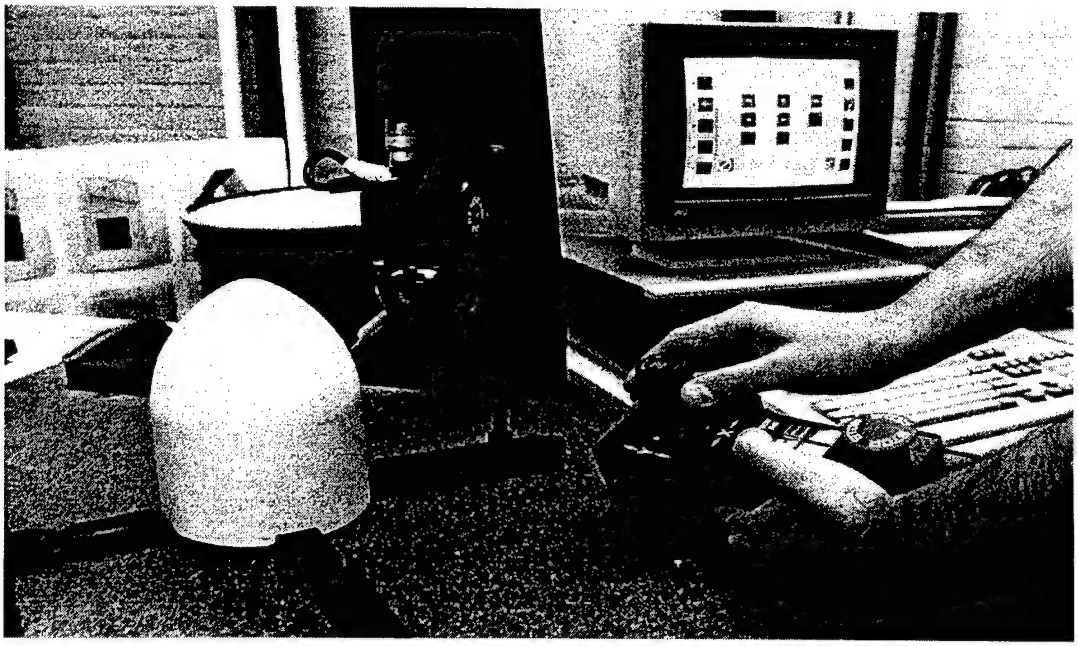


Figure 7 : (a)Electric Discharge Machining Center
(b)Close-up View of the EDM Sinker Head with Forming Die



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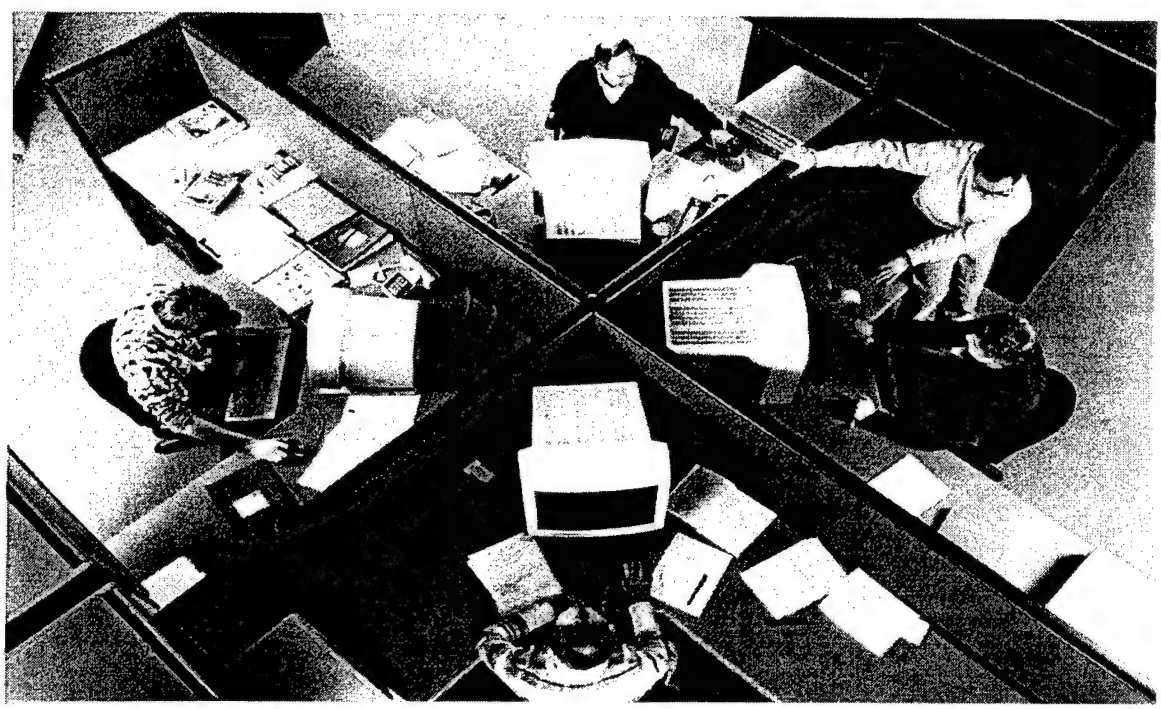

Figure 13: Partial view of the Computer-based Design Center on the Second Floor of the Carnegie Building

D. Establishment of Educational and Technology Transfer Mechanisms

1. Graduate Program in Concurrent Engineering

Stevens began a new initiative addressing the need to broaden the rate and extent to which concurrent engineering practices are implemented. As part of that effort a new multidisciplinary graduate program was developed offering both a Masters and Ph.D. degree in Concurrent Engineering.

The program was intended for students with an undergraduate degree in an engineering technical discipline. At the masters level, twelve courses are required consisting of a common core requirement of four courses followed by a choice of eight electives in various special areas of study. The core courses are:

CCE 601-602 : Principles of Concurrent Engineering I & II
CCE 621 –622: Quantitative Methods in Concurrent Engineering I & II
CCE 641 -642 : Principles of Product and Process Design I & II
CCE 661 –662: Concurrent Engineering Design Projects I & II

Electives may be chosen from any one of six academic departments at Stevens and include the following offerings:

Chemical Engineering

ChE 610 - Process Synthesis, Analysis & Design
615 Optimization in Chem. Engineering
673 Polymerization Engineering
674 Design of Polymer Processing Machinery
ChE 676 Polymer Mold and Die Design
677 Polymer Product Design & Control

Electrical Engineering/Computer Science

EE 520 Reliability Engineering
657 Robot Manipulation
658 Robot Vision
CS 641 Foundation of AI Theory with Applications
647 Designing and Developing Expert Systems
CR 657 Reliability and Quality

Management

Mgt 626 - Cost Analysis & Control
690 - An Intro. to Management of Business Organizations
761 - Analysis of Production

Materials and Metallurgical Engineering

Mt 520 - Composite Materials
643 - The Science of Ceramic Materials

Systems

771 - Management Information Systems

Applied Mathematics

Ma 644 - Methods of Operations Research

667 - Mathematical Prob. I

668 Mathematical Prob. II

Mechanical Engineering

ME 520 - Analysis and Design of Composites

552 - Manuf. Processes & Control

560 - Total Quality Control

564 - Principles of Optimum Design and Manufacture

596 - Thermal Analysis and Design in Electronic Packaging

598 - Introduction to Robotics

621 - Intro. to Modern Control

654 - Advanced Robotics

The majority of these graduate programs have been making full use of the new AMI facility.

2. Cooperative Education Program

In cooperation with the existing cooperative education program at Stevens, the AMI facility has also been used as an assigned work experience for undergraduates interested in pursuing the study of concurrent engineering. These undergraduates are being supported jointly by AMI funding under this contract and industrial sponsors. Having been educated in the practice and principles of concurrent engineering, they are capable of expediting the incorporation of these practices in specific industries.

3. Technology Transfer Program

The graduate degree program has been complemented by a technology transfer activity designed to accelerate the industrial use of concurrent engineering practice. This program includes the following features:

3.1 Engineer-in-residence positions

Engineer-in-residence positions have been created in the AMI. These appointments have been made available to engineers from industry wishing to pursue a graduate degree in concurrent engineering. In certain cases advanced degree candidates have served as adjunct faculty and taught selected graduate or undergraduate courses in manufacturing, design, materials, etc. Research projects of interest to industry are also being carried out, with industrial representation on the candidate's research committee.

3.2 Commercial hardware and software evaluation

The AMI is also serving as a demonstration facility for industrial users interested in evaluating new automation equipment, software, or advanced production techniques. Arrangements are also being made with various vendors of hardware and software to use the facility as a site for demonstrating their products.

E. List of Publications

1. "Functional Feature-Based Approximate Structural Analysis for Injection Molded LFRTP Parts", T. Xu, C. Chassapis, ANTEC'94.

2. "Concurrent Design Methodology for Injection Molded Parts," D.H. Sebastian, ANTEC '94.

3. "Function-Based Design for Injection Molding," D.H. Sebastian, ANTEC'93.

4. "Optimal Design of a Non-homogeneous Annular Disk Under Pressure Loadings," C-Y. Gau, S. Manoochehri, ASME Journal of Mechanical Design.

5. "A Knowledge-based Engineering System for the Design of Injection Molded Plastic Parts," S. Pratt, M. Sivakumar, S. Manoochehri, 1993 ASME Design Automation Conf., Albuquerque, NM.

6. "A Hybrid Shape Optimization Method Based on Implicit Differentiation Node Removal Techniques," P.Y. Shim, S. Manoochehri, 1993 ASME Design Automation Conf., Albuquerque, NM.

7. "Effect of Angle of Cut and Gap Size on the Shielding Effectiveness," B. Mottahed, S. Manoochehri, 1994 Intl Symposium in EMC, Sandia, Japan.

8. "An Intelligent Function-based Design System for Injection Molded Plastic Parts," S. Manoochehri, ANTEC'94.

9. "Algorithms to Detect Geometric Interactions in a Feature-based Design System," R. Talwar, S. Manoochehri, 1994 ASME Design Automation Conference.

10. "Predicting Allowable Draw Directions and Parting Line Locations for Molded Parts in a Feature-based Design System," M. Weinstein, S. Manoochehri, 1994 ASME Design AutomationConference.

11. "Configuration Design of Structures Using Discrete Optimization Approach," P.Y. Shim, S. Manoochehfi, 1994 ASME Design Automation Conference.

12. "A Feature-based Intelligent CAE Tool for the Design of Plastic Parts," M. Sivakumar, S. Manoochehri, 1994 ASME Winter Annual Meeting.

13. "Design for Cost of Plastic Injection Molded Parts," D.N. Merino, D.W. Merino, ANTEC'94.

14. "Design for Cost," D.N. Merino, D.W. Merino, 47th Northeast Quality Control Conf, ASQC.

15. "Injection Molding Process Development for Long Fiber Reinforced Thermoplastics," C. Gogos, CK Yoon, J. Brizzolara, ANTEC'94.

16. "A Device to Study Solids Compaction and Conveying in Single Screw Extrusion," C. Gogos, M. Zafar, D.H. Sebastian, D.B. Todd, ANTEC'94.

17. "Monitoring the Multiple Live Feed Injection Molding Process with Cavity Instrumentation," S. Parekh, S. Desai, J. Brizzolara, ANTEC'94.

18. "Shear Controlled Molding of Long Fiber Reinforced Thermoplastic Composites," S. Parekh, S. Desai, J. Brizzolara, ANTEC'93.

19. Flow Response and Microstructure of Polymers Reinforced with Discontinuous Fibers," T. Davidson, T.A. Huang, J. Brizzolara, D.H. Sebastian, Mat. Res. Soc. Symp. Proc.

20. "Pseudo-Laminate Analysis of Long Fiber Composites," A. Farouk, T. Davidson, ANTEC'94.

21. 'Effects of Glass and Carbon Fiber on Nylon 6,6, Crystallization," T. Davidson, T.A. Huang, J. Brizzolara, K. Siangchaew, M. Libera, Mat. Res. Soc. Symp. Proc..

22. "Concurrent Engineering Approach to Injection-Mold Design and Fabrication," V.B. Gerdes, D. Webb, C. Chassapis, ANTEC'94.

23. "Prototype Spray Metal Injection Mold for Long Fiber Reinforced Thermoplastic Parts," M. Cantwell, C. Chassapis, ANTEC'94.

24. "Computer-Aided Support Structure Design for Stereolithography Models," D. Webb, V.B. Gerdes, C. Chassapis, 5th Intl Corif on Rapid Prototyping, Dayton, Ohio.

25. "Configuration Aspects and Control of a Completely Integrated Manufacturing Cell," W.M. Goodman, C. Chassapis, S.J. Tricarno, 6th Intl Conf. on CAD/CAM, Robots & Factories of the Future.

26. "A Methodology for Computer Integration of CNC Machinery at Minimal Cost," C. Chassapis, W.M. Goodman, S.J. Tricamo, Autofact 91.